

# Patent Specification

<p style="text-align: center;">3</p> <p style="text-align: center;">DETAILED DESCRIPTION OF THE INVENTION</p> <p>FIG. 1 illustrates a magnetic recording system 10. A data source 12 supplies data to a write signal processing circuit</p>	<p style="text-align: center;">US 6,201,839 B1</p> <p style="text-align: center;">4</p> <p>the read-back waveform, sampled at the rate of one sample per symbol interval.</p> <p>When the written sequence of symbols <math>a_i, i=1, \dots, N</math>, is the read-back waveform is passed through a pulse-equalizing equalizer and sampled one sample per symbol, <math>i=1, \dots, N</math>. Due to noise in the sequence of samples <math>r_i, i=1, \dots, N</math>. Due to noise in the system, the samples <math>r_i</math> are realizations of random variables. The maximum likelihood detector determines the sequence of symbols <math>a_i</math> that has been written, by maximizing the likelihood function, i.e.,</p> $P(a_1, \dots, a_N) = \arg \max_{a_1, \dots, a_N} P(r_1, \dots, r_N   a_1, \dots, a_N) \quad (1)$ <p>the likelihood function <math>P(r_1, \dots, r_N   a_1, \dots, a_N)</math> is a joint probability density function (pdf) of the signal <math>r_1, \dots, r_N</math>, conditioned on the written symbols <math>a_1, \dots, a_N</math>. The maximization in (1) is done over all possible sequences of symbols in the sequence <math>\{a_1, \dots, a_N\}</math>.</p> <p>Due to the signal dependent nature of media noise in magnetic recording, the functional form of joint conditional pdf <math>P(r_1, \dots, r_N   a_1, \dots, a_N)</math> in (1) is different for different sequences <math>a_1, \dots, a_N</math>. Rather than making this maximization more complex but cluttered notation, the maximization is kept to a minimum by using simply the same symbol <math>P</math> to denote these different functions.</p> <p>By Bayes rule, the joint conditional pdf (likelihood function) is factored into a product of conditional pdfs:</p> $P(r_1, \dots, r_N   a_1, \dots, a_N) = \prod_{i=1}^N P(r_i   r_1, \dots, r_{i-1}, a_1, \dots, a_N) \quad (2)$ <p>To proceed and obtain more concrete results, the nature of the noise and of the intersymbol interference in magnetic recording is exploited.</p> <p>Finite correlation length. The conditional pdfs in Equation (2) are assumed to be independent of future samples after some length <math>L \geq 0</math>. <math>L</math> is the correlation length of the noise. This independence leads to:</p> $P(r_1, \dots, r_N   a_1, \dots, a_N) = P(r_1   a_1) P(r_2   a_1, a_2) \dots P(r_N   a_{N-L}, \dots, a_N) \quad (3)$ <p>Finite intersymbol interference. The conditional pdf is assumed to be independent of symbols that are not in the <math>K</math>-neighborhood of <math>r_n, \dots, r_{n+K}</math>. The value of <math>K \geq 1</math> is determined by the length of the intersymbol interference (ISI). For example, for PR4, <math>K=2</math>, while for EPR4, <math>K=3</math>. <math>K_1 \geq 0</math> is defined as the length of the leading (anticausal) ISI and <math>K_2 \geq 0</math> is defined as the length of the trailing (causal) ISI, such that <math>K=K_1+K_2+1</math>. With this notation the conditional pdf in (3) can be written as:</p> $P(r_1, \dots, r_N   a_1, \dots, a_N) = P(r_1   a_1) P(r_2   a_1, a_2) \dots P(r_N   a_{N-L}, \dots, a_N) \quad (4)$ <p>Substituting (4) into (2) and applying Bayes rule, the factored form of the likelihood function (conditional pdf) is obtained:</p>
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(12) **United States Patent**  
**Kavcic et al.**

(10) Patent No.: **US 6,201,839 B1**  
(45) Date of Patent: **Mar. 13, 2001**

(54) **METHOD AND APPARATUS FOR CORRELATION-SENSITIVE ADAPTIVE SEQUENCE DETECTION**

5,937,020 \* 8/1999 Hase et al. .... 375/376  
5,970,091 \* 10/1999 Nishida et al. .... 375/231  
5,978,426 \* 11/1999 Glover et al. .... 375/376

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OTHER PUBLICATIONS

Nakagawa et al., "A Study on Detection Methods of NRZ Recording". IEEE Trans. On Magnetics, vol. MAG-16, No.

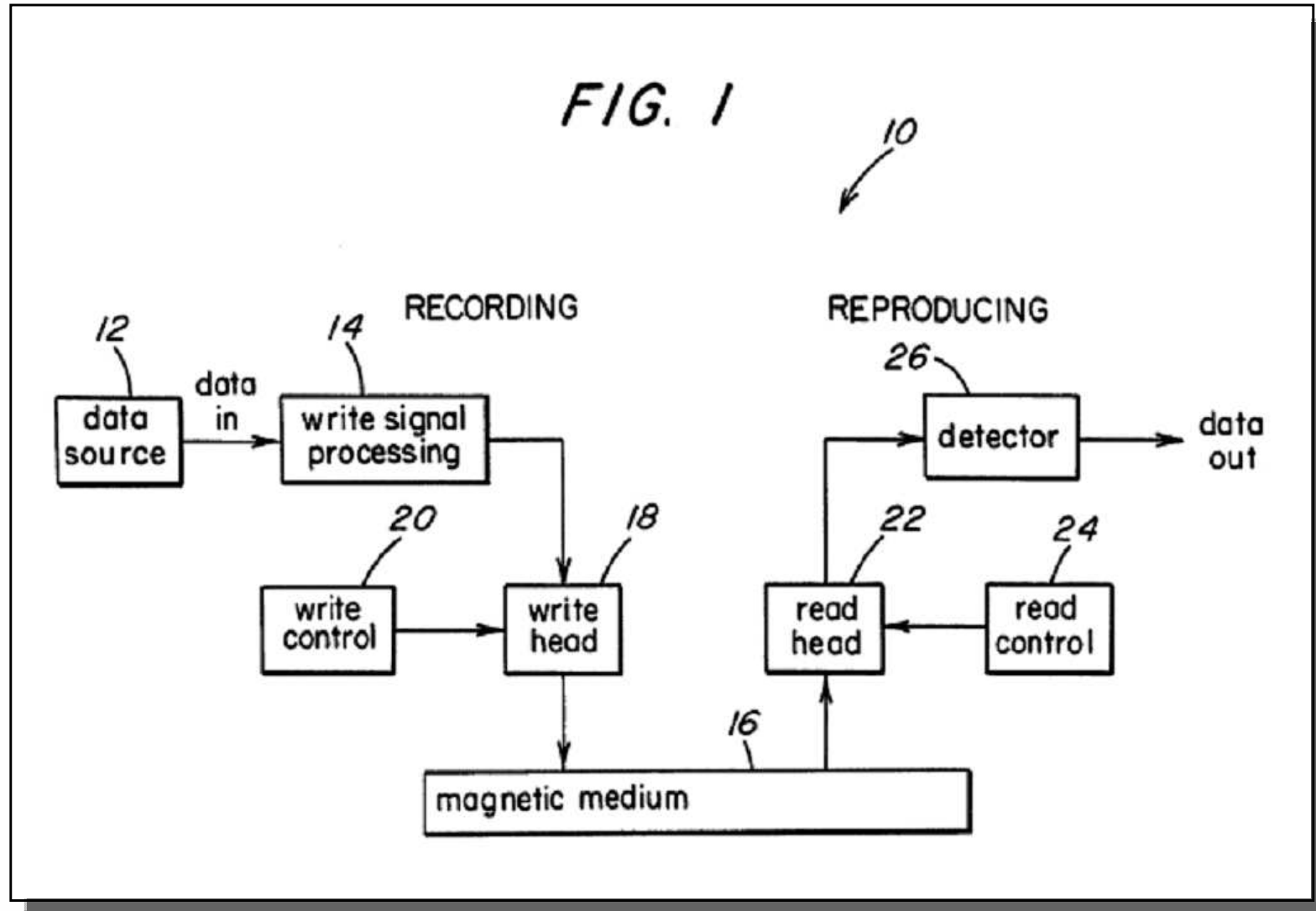
- Figures
- Branch Metrics
- Asserted Claims

shown in FIG. 2. The CS-MLSD detector circuit 28 is a part of the detector circuit 26 of FIG. 1. The detector circuit 28 has a feedback circuit 32 which feeds back into a Viterbi-like detector 30. The outputs of the detector 30 are decisions and delayed signal samples, which are used by the feedback circuit 32. A noise statistics tracker circuit 34 uses the delayed samples and detector decisions to update the noise statistics, i.e., to update the noise covariance matrices. A metric computation update circuit 36 uses the updated statistics to calculate the branch metrics needed in the Viterbi-like algorithm. The algorithm does not require replacing current detectors. It simply adds two new blocks in the feedback loop to adaptively estimate the branch metrics used in the Viterbi-like detector 30.

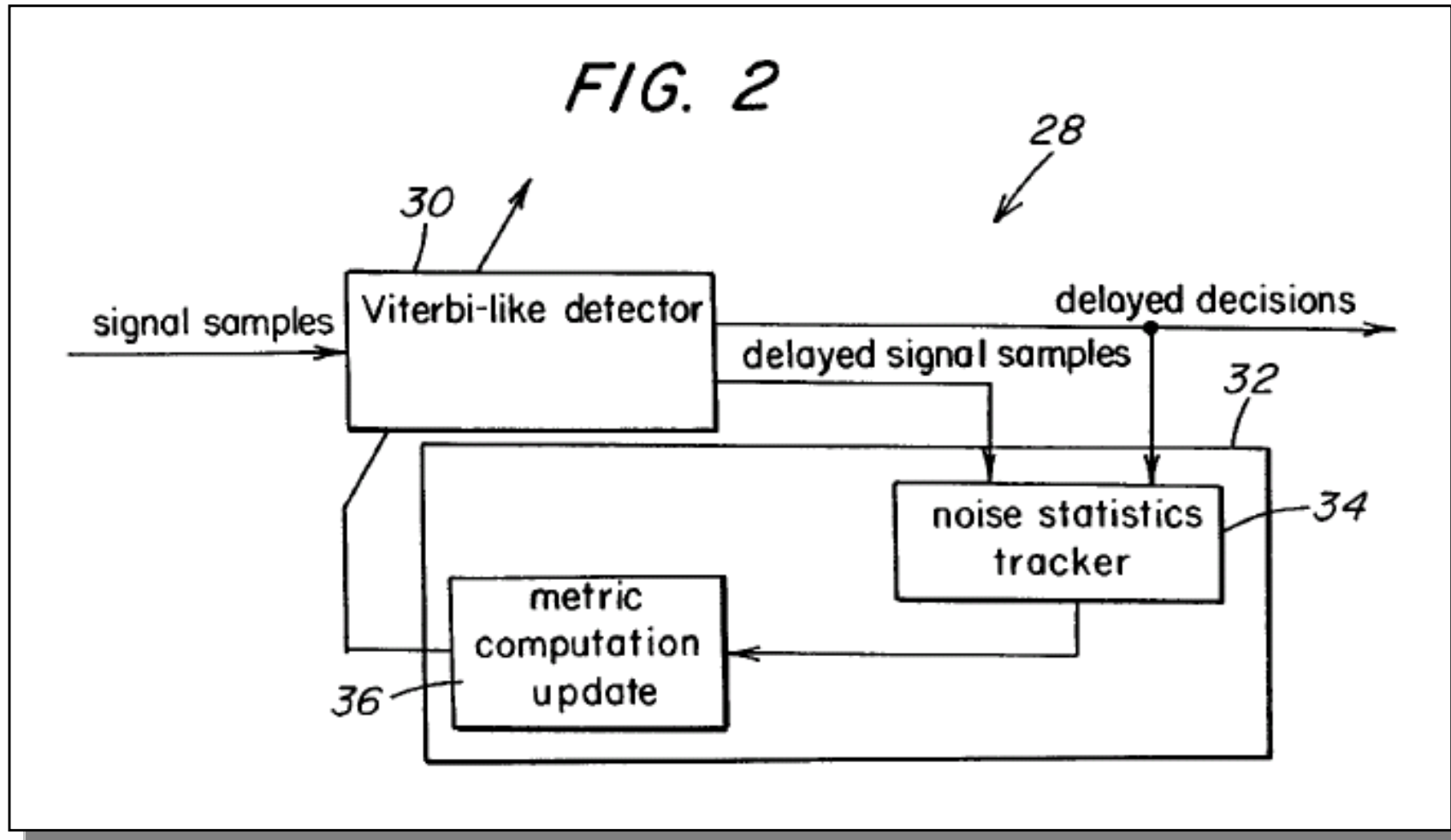
The Viterbi-like detector 30 typically has a delay associated with it. Until the detector circuit 28 is initialized, signals of known values may be input and delayed signals are not output until the detector circuit 28 is initialized. In other types of detectors, the detector may be initialized by having the necessary values set.

The correlation-sensitive maximum likelihood sequence detector (CS-MLSD) 28 is described hereinbelow. Assume that  $N \geq 1$  channel bits (symbols),  $a_1, a_2, \dots, a_N$ , are written on a magnetic medium. The symbols  $a_i, i=1, \dots, N$ , are drawn from an alphabet of four symbols,  $a_i \in \{+, \Phi, -, \ominus\}$ . The symbols '+' and '-' denote a positive and a negative transition, respectively. The symbol ' $\Phi$ ' denotes a written zero (no transition) whose nearest preceding non-zero symbol is a '+' while ' $\ominus$ ' denotes a written zero whose nearest preceding transition is a negative one, i.e., '-'. This notation is used because a simple treatment of transitions as '1's and no transitions as '0's is blind to signal asymmetries (MR head asymmetries and base line drifts), which is inappropriate for the present problem. In FIG. 3 a sample waveform is illustrated. The signal asymmetries and base line shifts are exaggerated in FIG. 3. FIG. 3 also shows the written symbols  $a_1, \dots, a_N$  as well as the samples  $r_1, \dots, r_N$  of

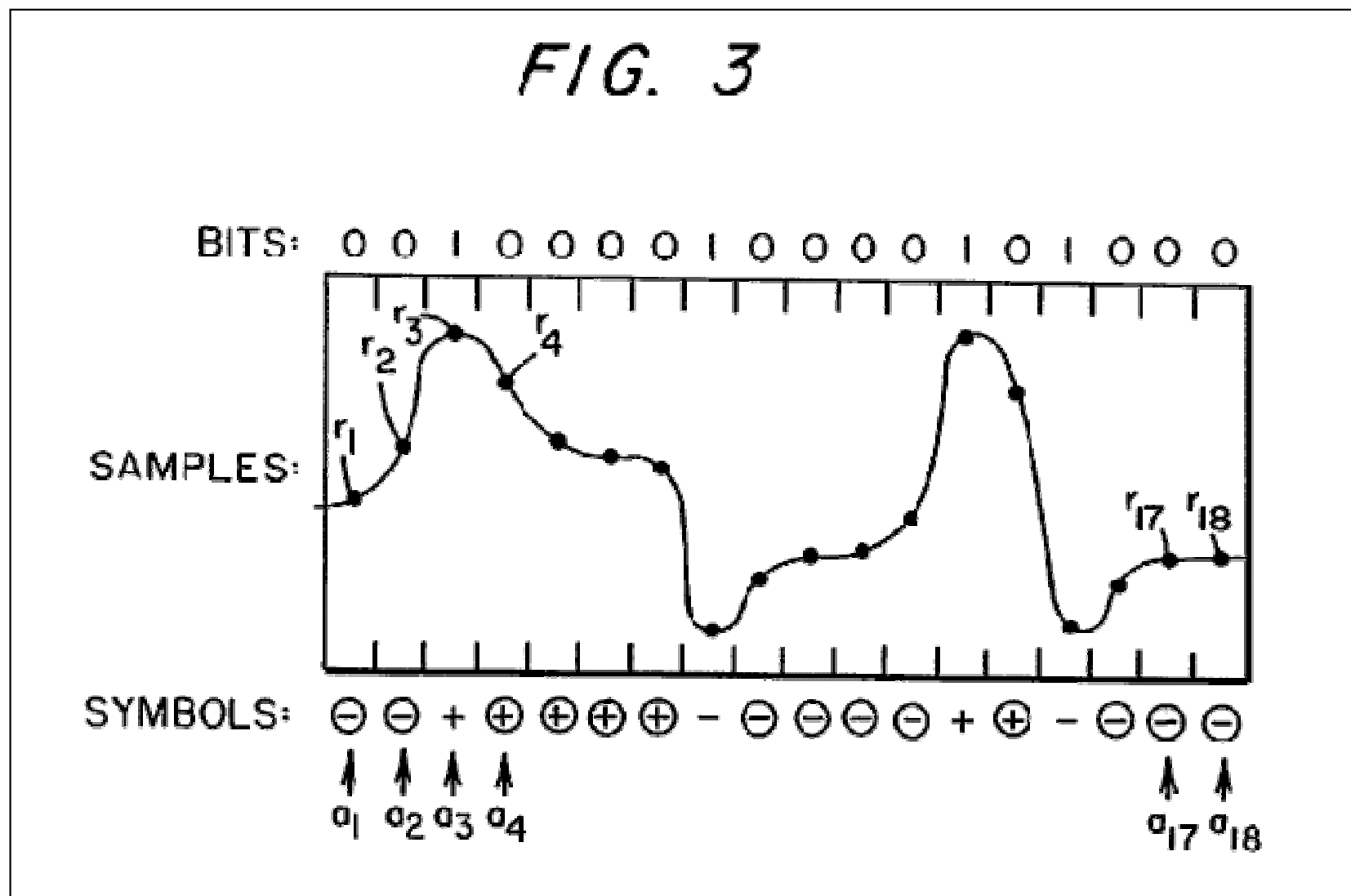
# Patent Figure 1: Magnetic Recording System



# Patent Figure 2: Detector Circuit

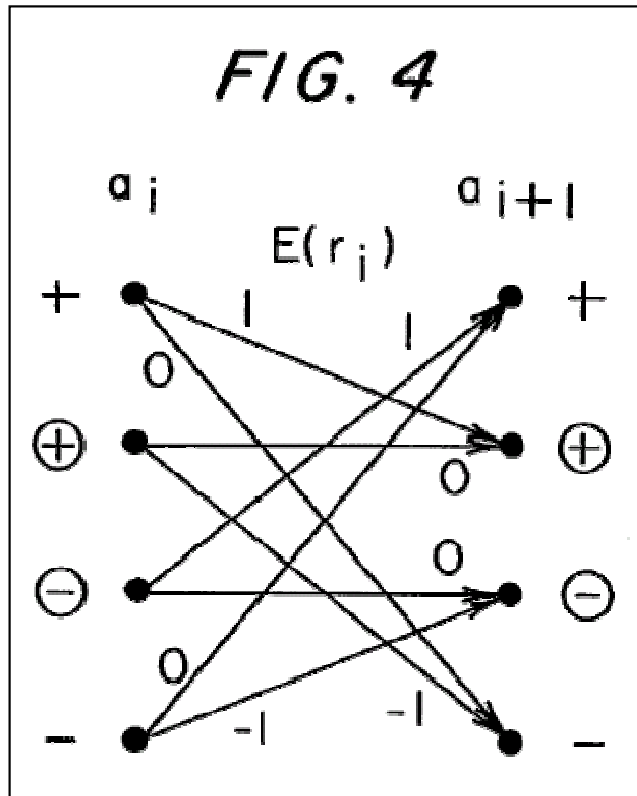


# Patent Figure 3: Signal Samples and Symbols

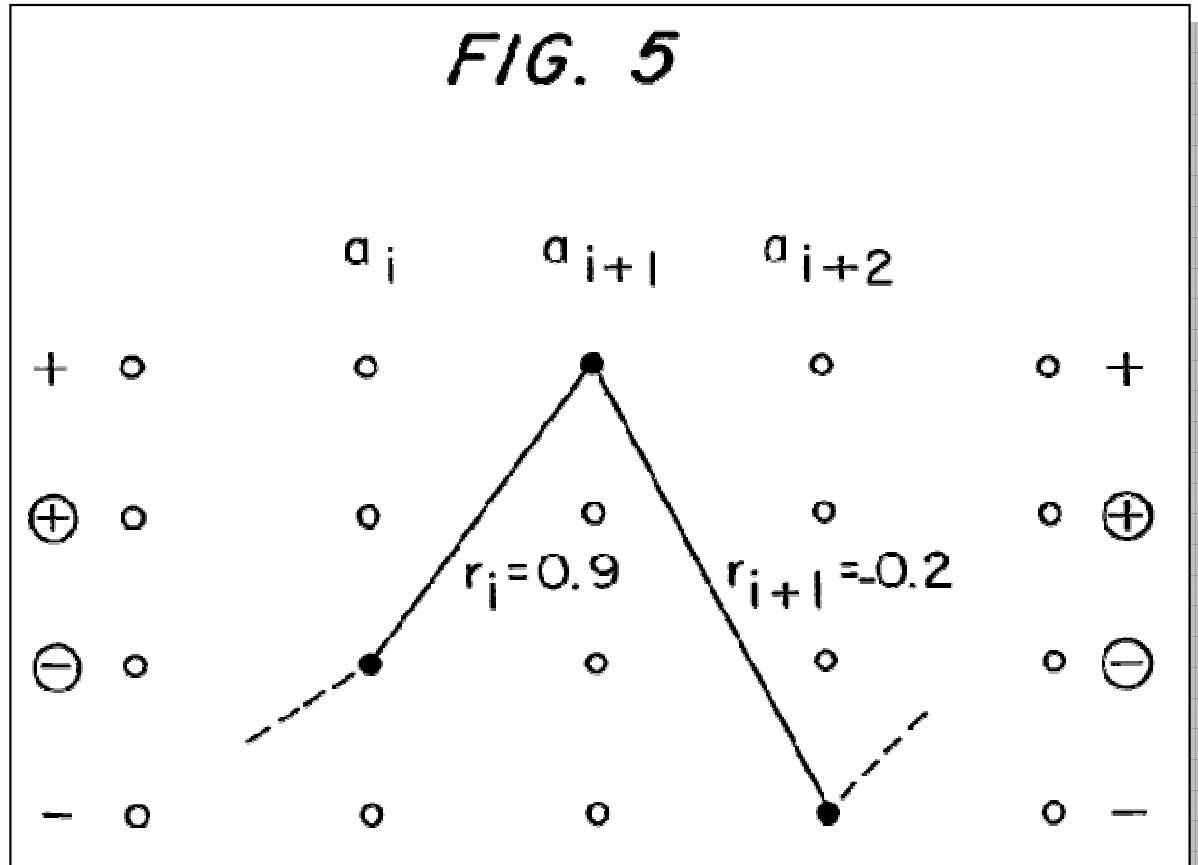


# Patent Figures 4 and 5: Trellis Diagrams

**FIG. 4**



**FIG. 5**



# Branch Metrics

- “Euclidean”

$$M_i = N_i^2 = (r_i - m_i)^2$$

Euclidian branch metric. In the simplest case, the noise samples are realizations of independent identically distributed Gaussian random variables with zero mean and variance  $\sigma^2$ . This is a white Gaussian noise assumption. This

(8)

- “Variance Dependent”

$$M_i = \log \sigma_i^2 + \frac{N_i^2}{\sigma_i^2} = \log \sigma_i^2 + \frac{(r_i - m_i)^2}{\sigma_i^2}$$

Variance dependent branch metric. It is again assumed that the noise samples are samples of independent Gaussian variables, but that their variance depends on the written sequence of symbols. The noise correlation length is still  $L=0$ , but the variance of the noise samples is no longer constant for all samples. The variance is  $\sigma_i^2$ , where the index  $i$  denotes the dependence on the written symbol sequence.

(10)

- “Correlation-Sensitive”

$$M_i = \log \det \frac{C_i}{\det c_i} + \underline{N}_i^T C_i^{-1} \underline{N}_i - \underline{n}_i^T c_i^{-1} \underline{n}_i$$

Correlation-sensitive branch metric. In the most general case, the correlation length is  $L>0$ . The leading and trailing ISI lengths are  $K_l$  and  $K_r$ , respectively. The noise is now considered to be both correlated and signal-dependent. Joint

(13)

# Correlation-Sensitive Branch Metric

- “Correlation-Sensitive”

$$M_i = \log \det \frac{C_i}{\det c_i} + \underline{N}_i^T C_i^{-1} \underline{N}_i - \underline{n}_i^T c_i^{-1} \underline{n}_i \quad (13)$$

$C_i$  → The  $(L+1) \times (L+1)$  matrix  $C_i$  is the covariance matrix of the data samples  $r_i, r_{i+1}, \dots, r_{i+L}$ , when a sequence of symbols  $a_{i-KL}, \dots, a_{i+L+KL}$  is written. The matrix  $c_i$  in the denominator of (11) is the  $L \times L$  lower principal submatrix of  $C_i = [c_i]$ . The  $(L+1)$ -dimensional vector  $\underline{N}_i$  is the vector of differences between the observed samples and their expected values when the sequence of symbols  $a_{i-KL}, \dots, a_{i+L+KL}$  is written, i.e.:

$\underline{N}_i$  → 
$$\underline{N}_i = [(r_i - m_i)(r_{i+1} - m_{i+1}) \dots (r_{i+L} - m_{i+L})]^T \quad (12)$$

$\underline{n}_i$  → The vector  $\underline{n}_i$  collects the last  $L$  elements of  $\underline{N}_i$ , 
$$\underline{n}_i = [(r_{i+1} - m_{i+1}) \dots (r_{i+L} - m_{i+L})]^T.$$

'839 Patent at 6:53-65

# Patent Figure 3A: Metric Computation Circuit

- “Correlation-Sensitive”

$$M_i = \log \det \frac{C_i}{\det c_i} + \underline{N}_i^T C_i^{-1} \underline{N}_i - \underline{n}_i^T c_i^{-1} \underline{n}_i \quad (13)$$

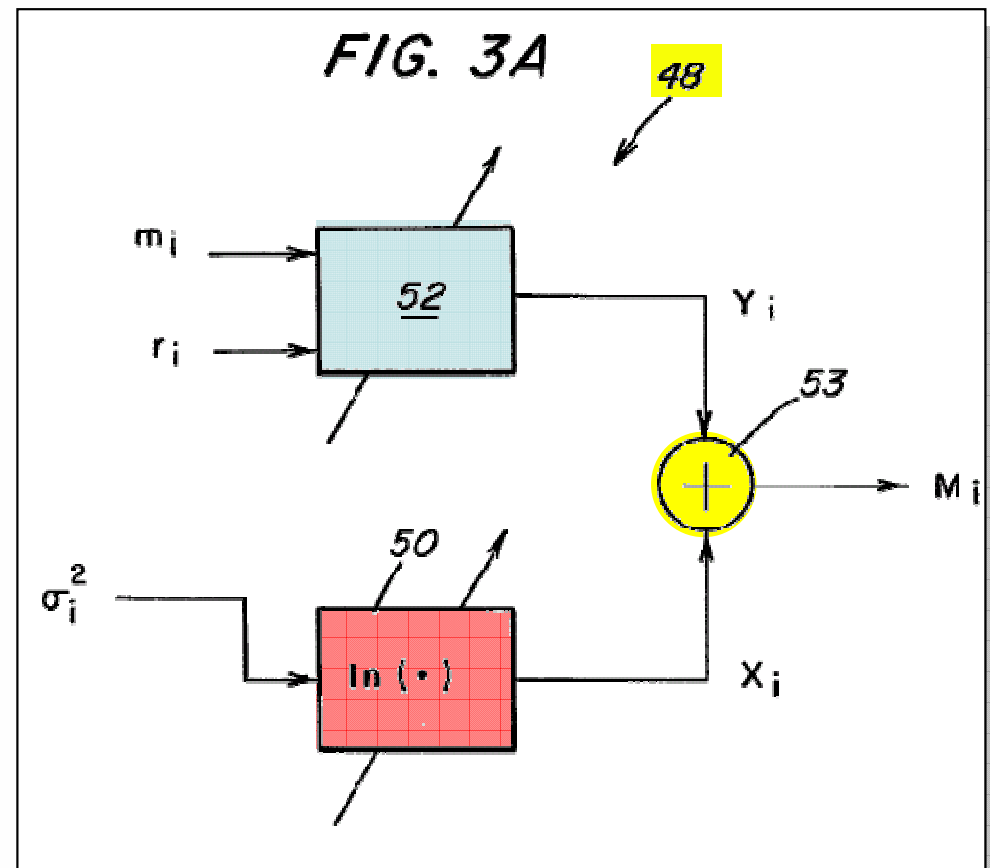
FIG. 3A illustrates a block diagram of a branch metric computation circuit 48 that computes the metric  $M_i$  for a branch of a trellis, as in Equation (13). Each branch of the trellis requires a circuit 48 to compute the metric  $M_i$ .

A logarithmic circuit 50 computes the first term of the right hand side of (13)

$$\left( \text{i.e. } \log \frac{\det C_i}{\det c_i} \right)$$

and a quadratic circuit 52 computes the second terms of the right hand side of (13) (i.e.  $\underline{N}_i^T C_i^{-1} \underline{N}_i - \underline{n}_i^T c_i^{-1} \underline{n}_i$ ). The arrows through the circuits 50 and 52 represent the adaptive nature of the Viterbi-like detector 30. A sum circuit 53 computes the sum of the outputs of the circuits 50 and 52.

'839 Patent 7:10-24





# Summary of Asserted Claims: Two Groups

Asserted Claim	Group I: No “noise covariance matrices” requirement	Group II: Requires “updating . . . noise covariance matrices”
‘839 Patent, cl. 1	✓	
cl. 4	✓	
cl. 11		✓
cl. 16		✓
cl. 19		✓
cl. 23		✓
‘180 Patent, cl. 1	✓	
cl. 6		✓

# Group I: '839 Patent Claim 1

1. A method of determining branch metric values for branches of a trellis for a Viterbi-like detector, comprising:
  - [1] selecting a branch metric function for each of the branches at a certain time index; and
  - [2] applying each of said selected functions to a plurality of signal samples to determine the metric value corresponding to the branch for which the applied branch metric function was selected, wherein each sample corresponds to a different sampling time instant.

# Group I: '839 Patent Claim 1

1. A method of determining **branch metric values** for **branches** of a **trellis** for a **Viterbi-like** detector, comprising:

[1] **selecting** a **branch metric function** for each of the **branches** at a **certain time index**; and

[2] applying each of said **selected functions** to a plurality of **signal samples** to determine the **metric value** corresponding to the **branch** for which the applied **branch metric function** was **selected**, wherein **each sample corresponds to a different sampling time instant**.

*[“Agreed to” terms in **blue**; “disputed” terms in **red**]*

# Group I: '839 Patent Claim 4

4. A method of determining branch metric values for branches of a trellis for a Viterbi-like detector, comprising:

[1] selecting a branch metric function for each of the branches at a certain time index from a set of signal-dependent branch metric functions; and

[2] applying each of said selected functions to a plurality of signal samples to determine the metric value corresponding to the branch for which the applied branch metric function was selected, wherein each sample corresponds to a different sampling time instant.

# Group I: '180 Patent Claim 1

1. A method of determining **branch metric values** in a detector, comprising:
  - [1] receiving a plurality of time variant **signal samples**, the **signal samples** having one of **signal-dependent noise**, **correlated noise**, and both **signal dependent** and **correlated noise** associated therewith;
  - [2] selecting a **branch metric function** at a **certain time index**; and
  - [3] applying the selected function to the **signal samples** to determine the **metric values**.

## Group II: '839 Patent Claim 19

19. A detector circuit for detecting a plurality of data from a plurality of signal samples read from a recording medium, comprising:

- a Viterbi-like detector circuit, said Viterbi-like detector circuit for producing a plurality of delayed decisions and a plurality of delayed signal samples from a plurality of signal samples;

- a noise statistics tracker circuit responsive to said Viterbi-like detector circuit for updating a plurality of noise covariance matrices in response to said delayed decisions and said delayed signal samples; and

- a correlation-sensitive metric computation update circuit responsive to said noise statistics tracker circuit for recalculating a plurality of correlation-sensitive branch metrics from said noise covariance matrices, said branch metrics output to said Viterbi-like detector circuit.

## Group II: '839 Patent Claim 19

19. A detector circuit for detecting a plurality of data from a plurality of **signal samples** read from a recording medium, comprising:

- a **Viterbi-like detector circuit**, said **Viterbi-like detector circuit** for producing a plurality of delayed decisions and a plurality of delayed **signal samples** from a plurality of **signal samples**;

- a **noise statistics tracker circuit** responsive to said **Viterbi-like detector circuit** for updating a plurality of **noise covariance matrices** in response to said delayed decisions and said delayed **signal samples**; and

- a **correlation-sensitive metric computation update circuit** responsive to said **noise statistics tracker circuit** for recalculating a plurality of **correlation-sensitive branch metrics** from said **noise covariance matrices**, said **branch metrics** output to said **Viterbi-like detector circuit**.

# Group II: '839 Patent Claim 11

11. A method of detecting a sequence that exploits the **correlation** between **adjacent signal samples** for adaptively **detecting a sequence of symbols** stored on a high density magnetic recording device, comprising the steps of:
- (a) performing a **Viterbi-like sequence detection** on a plurality of **signal samples** using a plurality of **correlation sensitive branch metrics**;
  - (b) outputting a delayed decision on **the recorded symbol**;
  - (c) outputting a delayed **signal sample**;
  - (d) adaptively updating a plurality of **noise covariance matrices** in response to said delayed **signal samples** and said delayed decisions;
  - (e) recalculating said plurality of **correlation-sensitive branch metrics** from said **noise covariance matrices** using subsequent **signal samples**; and
  - (f) repeating steps (a)-(e) for every new **signal sample**.



# Group II: '839 Patent Claim 16

16. A method of detecting a sequence that exploits the **correlation** between **adjacent signal samples** for adaptively **detecting a sequence of symbols** through a communications channel having **intersymbol interference**, comprising the steps of:
- (a) performing a **Viterbi-like sequence detection** on a plurality of **signal samples** using a plurality of **correlation sensitive branch metrics**;
  - (b) outputting a delayed decision on the transmitted symbol;
  - (c) outputting a delayed **signal sample**;
  - (d) adaptively updating a plurality of **noise covariance matrices** in response to said delayed **signal samples** and said delayed decisions;
  - (e) recalculating said plurality of **correlation-sensitive branch metrics** from said **noise covariance matrices** using subsequent **signal samples**; and
  - (f) repeating steps (a)-(e) for every new **signal sample**.

# Group II: '839 Patent Claim 23

23. A system for recording information on a magnetic medium, comprising:

- [1] a **write signal processing circuit** for processing a plurality of data from a data source;
- [2] a **write control circuit**;
- [3] a **write head** responsive to said **write control circuit** for receiving a plurality of signals from said **write signal processing circuit**, said **write head** for writing said signals to the recording medium;
- [4] a **read control circuit**;
- [5] a **read head** for reading said signals from the recording medium, said **read head** responsive to said **read control circuit**; and
- [6] a detector circuit for detecting a plurality of data from said read signals, said detector comprising:
  - [7] a **Viterbi-like detector circuit**, said **Viterbi-like detector circuit** for producing a plurality of delayed decisions and a plurality of delayed **signal samples** from a plurality of **signal samples**;
  - [8] a **noise statistics tracker circuit** responsive to said **Viterbi-like detector circuit** for updating a plurality of **noise covariance matrices** in response to said delayed decisions and said delayed **signal samples**; and
  - [9] a **correlation-sensitive metric computation update circuit** responsive to said **noise statistics tracker circuit** for recalculating a plurality of **correlation-sensitive branch metrics** from said **noise covariance matrices**, said **branch metrics** output to said **Viterbi-like detector circuit**.

## Group II: '180 Patent Claim 6

6. A method of detecting a sequence that exploits a **correlation** between adjacent **signal samples** for adaptively **detecting a sequence of symbols** through a communications channel having **intersymbol interference**, comprising:
- (a) performing sequence detection on a plurality of **signal samples** using a plurality of **correlation sensitive branch metrics**;
  - (b) outputting a delayed decision on the transmitted symbol;
  - (c) outputting a delayed **signal sample**;
  - (d) adaptively updating a plurality of **noise covariance matrices** in response to the delayed **signal samples** and the delayed decisions;
  - (e) recalculating the plurality of **correlation sensitive branch metrics** from the **noise covariance matrices** using subsequent **signal samples**; and
  - (f) repeating steps (a)-(e) for every new **signal sample**.

# Appendix: Claim Terms

- Undisputed Groupings
  - Read/Write Head
  - Noise
  - Signal Samples
  - Sequences and Symbols
  - Branch Metrics
  - Viterbi-Like
- Eight (8) Disputed Claim Terms

# Undisputed Claim Terms: Read/Write Heads

read control circuit	“Read control circuit” means “a circuit that controls the position of a read head with respect to a magnetic medium.”
read head	“Read head” means “a magnetic device that reads (or retrieves) signals from a magnetic medium, that are stored on the medium as a series of variations in magnetic flux.”
write control circuit	“Write control circuit” means “a circuit that controls the position of the write head with respect to a magnetic medium.”
write head	“Write head” means “a magnetic device that writes (or stores) signals to a magnetic medium as a series of variations in the magnetic flux of the medium.”
write signal processing circuit	“Write signal processing circuit” means “a circuit that converts data into signals with a format suitable for storage on a magnetic medium.”

# Undisputed Claim Terms: Noise

noise	“Noise” means “an unwanted disturbance in a signal.”
noise statistics tracker circuit	“Noise statistics tracker circuit” means “a circuit that tracks noise statistics.”

# Undisputed Claim Terms: Signal Samples

adjacent [signal samples]	“Adjacent signal samples” means “‘signal samples’ from consecutive points in time.”
certain time index	“Certain time index” means “a certain point in time.”
each sample corresponds to a different sampling time instant	“Each sample corresponds to a different sampling time instant” means “each ‘signal sample’ is from a different point in time.”
signal sample	“Signal sample” means “a value of a signal at a certain point in time.”

# Undisputed Claim Terms: Sequences and Symbols

intersymbol interference	“Intersymbol interference” means “a form of distortion of a signal in which symbols interfere with neighboring symbols.”
sequence detection	“Sequence detection” means “detection of a sequence of symbols.”
the recorded symbol	“The recorded symbol” refers to “the symbol stored on a high density magnetic recording device” of the preamble of claim 11 of the ‘839 patent.



# Undisputed Claim Terms: Branch Metrics

branch	<p>“Branch” means “a potential transition between two states (nodes) immediately adjacent in time in a ‘trellis.’”</p> <p>Examples of branches are illustrated as the lines between the nodes in Figure 4 of the 839 patent.</p>
branch metric function	<p>“Branch metric function” means “a mathematical function for determining a ‘branch metric value’ for a ‘branch.’”</p>
branch metric value / branch metric / metric value	<p>“Branch metric value,” “branch metric,” and “metric value” mean “the numerical value of a ‘branch.’”</p>
selecting a [branch metric function] selecting a [branch metric function] . . . from a set	<p>“Selecting” means “to choose one from a set of more than one.”</p>
trellis	<p>“Trellis” means “a graphical representation of the progression of states of a communications channel in time, wherein states are depicted as nodes and potential transitions between states are depicted as lines or arrows.”*</p> <p>An example of a trellis is illustrated in Figure 4 of the 839 patent.</p> <p>* The parties agree that the phrase “progression of states of a communications channel” is not intended to limit the channel to any particular channel.</p>

# Undisputed Claim Terms: Viterbi-Like

Viterbi-like	“Viterbi-like” means “similar to and including the ‘Viterbi algorithm.’”
Viterbi-like detector [circuit]	“Viterbi-like detector” and “Viterbi-like detector circuit” mean “a detector that uses a ‘Viterbi-like’ algorithm.”
Viterbi-like sequence detection	“Viterbi-like sequence detection” means “detection of a sequence of symbols using a ‘Viterbi-like’ algorithm.”

# Eight (8) Disputed Claim Terms

Term No.	CMU's Construction	Marvell's Construction
<b>No. 1:</b> correlation	the degree to which two more items (here, noise in signal samples) show a tendency to vary together.	the expected (mean) value of the product of two random variables (e.g., $E[r_i r_j]$ , where $r_i$ and $r_j$ are signal samples at time $i$ and time $j$ , respectively).
<b>No. 2:</b> covariance	none	the expected (mean) value of the product of $(r_i - m_i)$ and $(r_j - m_j)$ , where $r_i$ and $r_j$ are observed signal samples (at time $i$ and time $j$ , respectively) and $m_i$ and $m_j$ are the expected (mean) values of the samples (at time $i$ and time $j$ , respectively) (i.e., $E[(r_i - m_i)(r_j - m_j)]$ ).
<b>No. 3:</b> covariance matrix	none	arrays of covariances of pairs of signal samples, e.g.: $\begin{bmatrix} \text{cov}(r_i, r_i) & \text{cov}(r_i, r_{i+1}) \\ \text{cov}(r_{i+1}, r_i) & \text{cov}(r_{i+1}, r_{i+1}) \end{bmatrix}$
<b>No. 4:</b> noise covariance matrices	noise statistics used to calculate the 'correlation-sensitive branch metrics.'	covariance matrices of signal samples (where the signal samples include noise).
<b>No. 5:</b> correlated noise	noise with 'correlation' among 'signal samples,' such as that caused by coloring by front-end equalizers, media noise, media nonlinearities, and magnetoresistive (MR) head nonlinearities.	noise having nonzero 'covariance' (see construction of 'covariance' above).

# Eight (8) Disputed Claim Terms

Term	CMU's Construction	Marvell's Construction
<b>No. 6:</b> signal-dependent noise	media noise in the readback signal whose noise structure is attributable to a specific sequence of symbols (e.g., written symbols).	noise that is dependent on the signal.
<b>No. 7:</b> signal-dependent branch metric function	a “branch metric function” that accounts for the signal-dependant structure of the media noise.	a “branch metric function” that accounts for “signal-dependent noise.”
<b>No. 8:</b> Viterbi [algorithm]	an algorithm that uses a trellis to determine the best sequence of hidden states (in this case, written symbols) based on observed events (in this case, observed readings that represent the written symbols), where the determined sequence is indicated by the best path through the trellis.	an algorithm that uses a trellis to perform sequence detection by calculating branch metrics for each branch of the trellis, comparing the accumulated branch metrics for extensions of retained paths leading to each node of the trellis at a given time, and for each node, retaining only the path having the best accumulated metric.